

Pathways to Rare Baryonic B Decays

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Abstract

We point out new ways to search for charmless baryonic B decays: baryon pair production in association with η' is very likely as large as or even a bit larger than two body $K\pi/\pi\pi$ modes. We extend our argument, in weaker form, to $B \rightarrow \gamma + X_s$ and $\ell\nu + X$. Although calculations are not reliable, estimates give branching ratios of order 10^{-5} – 10^{-6} , where confidence is gained from recent experimental finding that $B \rightarrow D^*p\bar{n}$, $D^*p\bar{p}\pi$ are not far below $D^*\pi$ and $D^*\rho$ rates. Observation of charmless baryon modes would help clarify the dynamics of weak decays to baryonic final states, while the self-analyzing prowess of the Λ -baryon can be helpful in CP - and T -violation studies.

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Many charmless mesonic $B \rightarrow M_{(s)}\bar{M}$ decays have emerged at the 10^{-5} level in recent years, giving evidence for strong $b \rightarrow s$ penguins and tree level $b \rightarrow u$ transitions. In contrast, the search for rare baryonic modes has been less fruitful. The most recent limits [1] are $B \rightarrow \bar{\Lambda}p$, $\bar{\Lambda}p\pi^-$ and $\bar{p}p < 0.26, 1.3$ and 0.7×10^{-5} , respectively, improving previous bounds [2] by more than an order of magnitude, except for the $p\bar{p}$ mode which has a 2.8σ excess. Theoretical work on rare baryonic (we use M and \mathbf{B} to stand for meson and baryon, respectively) decay is equally sparse [3–6], but in general they predict $B \rightarrow \bar{\mathbf{B}}_{(s)}\mathbf{B}$ to be below 10^{-5} , oftentimes considerably below. With the advent of B factories, two body baryonic modes should eventually emerge. But one may wonder: Where is the best place to search for charmless baryonic modes?

We suggest that charmless baryon-antibaryon final states in B decays may show up in association with η' and/or γ with sizeable branching ratios, i.e. $\approx 10^{-5} - 10^{-6}$ or more. Although theoretical calculations are very unreliable, the bright side of this is that theory will learn much from experiment once the measurements become available. In particular, we would get important input for understanding the dynamics of weak decays. Furthermore, baryonic final states offer new observables that should be sensitive probes of CP and T violation.

We take cue from the surprise discovery of the $B \rightarrow \eta' + X$ modes. Without guidance from theory, the CLEO Collaboration discovered that both inclusive [7] $B \rightarrow \eta' + X_s$ (where $X_s = K + n\pi$) and exclusive [8] $B \rightarrow \eta'K$ modes are very large ($> 6 \times 10^{-4}$ and $\simeq 8 \times 10^{-5}$, respectively). To date they are still not clearly understood. Theoretical work done after the fact [9] can still not fully explain the exclusive rate even by some *ad hoc* tuning of parameters. For the inclusive mode, an interesting but still controversial proposal [10,11], based on $b \rightarrow sg^*$ followed by $g^* \rightarrow g\eta'$ transition (which is motivated by the gluon anomaly), seems to account for the observed m_{X_s} recoil spectrum and rate. In the following, we give two semi-quantitative arguments, one from the inclusive perspective with the anomaly mechanism, the other from exclusive perspective and based on a pole model, that suggest $B \rightarrow \eta'\mathbf{B}_s\mathbf{B}(\pi)$ [12] may be comparable to the $\eta'K$ modes with $Br \sim 10^{-5}$. Interestingly,

our suggestion is supported by the very recent observation [13] of $B \rightarrow D^* p \bar{n}$ and $D^* p \bar{p} \pi$ modes with rates not far below $B \rightarrow D^* \pi$, $D^* \rho$.

The partial reconstruction technique used in inclusive $B \rightarrow \eta' + X_s$ study was initially developed for inclusive $b \rightarrow s \gamma$ [14] studies. Since both the inclusive $b \rightarrow s \gamma \sim 3 \times 10^{-4}$ and exclusive $B \rightarrow K^* \gamma \simeq 4 \times 10^{-5}$ [15] are comparable to their η' counterparts, we extend the pole model argument and suggest that $B \rightarrow \gamma \bar{\mathbf{B}}_s \mathbf{B}(\pi)$ may also be promising. Similar arguments suggest that $B \rightarrow \ell \nu \bar{\mathbf{B}} \mathbf{B}(\pi)$ should also be searched for. We also comment on the special case of $B \rightarrow J/\psi \bar{\mathbf{B}}_s \mathbf{B}$ [16], where phase space is extremely limited.

Let us understand why $B \rightarrow \bar{\mathbf{B}}_{(s)} \mathbf{B}(\pi)$ modes are so suppressed. Baryon formation in B decays is more difficult than the mesonic case, as reflected in model calculations. In pole models [3,4], the strong $B \rightarrow \bar{\mathbf{B}}_b \mathbf{B}_1$ transition (\mathbf{B}_b is a b -baryon) is followed by a $\bar{\mathbf{B}}_b \rightarrow \bar{\mathbf{B}}_2$ weak transition, where the large imbalance in mass is the main source of uncertainty. The estimate of transitions to final states involving spin 3/2 baryons [4] seem to be ruled out by experiment already [1]. Another intuitive picture involves diquarks, which we denote generically as \mathbf{D} . One first has a $b \rightarrow \mathbf{D}_1 \bar{q}$ weak decay [5], which, together with the spectator quark, gives a $\mathbf{D}_1 \bar{\mathbf{D}}_2$ pair. Further creation of a $\bar{q}q$ pairs leads to a $\bar{\mathbf{B}} \mathbf{B}$ final state. However, since the energy release in B decays is so much larger than the argued color $\bar{3}$ diquark binding scale ~ 1 GeV, the approach is dubious for charmless two body final states. Finally, the QCD sum rule approach [6] tries to evaluate directly the B - $\bar{\mathbf{B}}_{(s)}$ - \mathbf{B} three point function, and it is the only method that has studied penguin effects so far. The basic problem may be the applicability of sum rules to B decay to light hadrons. Analogous to the diquark picture, one relies on a soft \bar{q} - q pair creation model, hence it seems to be better suited for $B \rightarrow \bar{\mathbf{B}}_c \mathbf{B}$ processes where the energy release is lower.

We can now understand why $B \rightarrow \bar{\mathbf{B}}_{(s)} \mathbf{B}$ modes are suppressed compared to $B \rightarrow M_{(s)} \bar{M}$: Baryons are more complicated objects than the “atomic” mesons and hence harder to form. The weak Hamiltonian induces $\bar{b} \rightarrow \bar{d} q \bar{q}$ and $\bar{s} q \bar{q}$ transitions that lead to final states already containing two $q \bar{q}$ pairs, typically with matching color that project easily onto $M_{(s)} \bar{M}$ final states. In contrast, not all the ingredients are present for the $B \rightarrow \bar{\mathbf{B}}_{(s)} \mathbf{B}$ case. The need for

creating another $q\bar{q}$ pair leads to suppression by either a strong coupling, or by the intrinsic softness of nonperturbative pair creation against the rather hard weak decay.

Applying the diquark model to penguin processes serves to illustrate further the point. The penguin process can be viewed as induced by a $b \rightarrow sg^*$ transition where g^* is virtual. One may think that $g^* \rightarrow \bar{\mathbf{D}}\mathbf{D}$ can be treated on the same footing as $g^* \rightarrow q\bar{q}$, hence $b \rightarrow s\bar{\mathbf{D}}\mathbf{D}$ could be analogous to $b \rightarrow s\bar{q}q$. However, the picture fails because, while quarks are truly fundamental, diquarks are quark-quark correlations at best up to typical hadronic scale. Since the g^* virtuality in two body penguin transitions is well above this scale, the $g^* \rightarrow \bar{\mathbf{D}}\mathbf{D}$ transition is suppressed by some form factor. Thus, the smallness of $B \rightarrow \bar{\mathbf{B}}_{(s)}\mathbf{B}$ modes is rooted in the large energy release. They are further suppressed compared to $B \rightarrow M_{(s)}\bar{M}$ modes because of the more complicated composition of baryons.

From discussions above, we have gained some insight into where charmless baryonic B decays may be larger: *One has to reduce the energy release and at the same time allow for baryonic ingredients to be present in the final state.* A natural starting point is the inclusive $B \rightarrow \eta' + X_s$ decay, where a large rate of $\simeq 6 \times 10^{-4}$ is observed for $p_{\eta'} > 2.0$ GeV. Much energy is already carried away by the η' while the signal is established by requiring a cut [7] on recoil system mass $m_{X_s} < 2.35$ GeV. The observed inclusive m_{X_s} spectrum is so far accounted for only by the anomaly mechanism [10,11], namely $b \rightarrow sg^*$ followed by $g^* \rightarrow g\eta'$ with effective coupling motivated by the gluon anomaly. It has been argued that the anomaly coupling should be form factor suppressed [17] since the g^* is rather virtual ($\sqrt{q^2} \sim 3$ GeV). However, the problem is interestingly nontrivial [11] because of high gluon binding scale in the $G_{\mu\nu}\tilde{G}_{\mu\nu}$ channel, which has no analog in the $\gamma^* \rightarrow \gamma\pi$ case. At any rate, we take this as a model that is rather effective in producing fast η' in B decays. We therefore consider the transition $\bar{b}q \rightarrow \eta' + \bar{s}gq$ where $\bar{s}gq$ forms a color singlet.

Treating the gluon as a parton in the final state, the $\bar{s}gq$ system gives an m_{X_s} recoil mass spectrum that is in good agreement with data [7] and peaks roughly at 2.3 GeV. Although $\bar{s}gq$ clearly can evolve into $K + n\pi$, it is instructive to visualize how it may feed a single kaon. In Ref. [11] an effective $m_g = 0.5$ GeV was used in final state phase space to remove

“soft” gluons (below constituent $q\bar{q}$ threshold). Since there are no infrared singularities, it was pointed out that the m_{X_s} region covered by $m_g \lesssim 0.5$ GeV might be swept under the kaon, and could by itself account for the observed size of $B \rightarrow \eta' K$. Such “ $|\bar{s}gq\rangle$ Fock component of the K meson” contributions to $B \rightarrow \eta' K$ have not been taken into account in the traditional approach [9]. Here we extend this observation and exploit $g^* \rightarrow \bar{\mathbf{D}}\mathbf{D}$ diquark pair creation to construct baryonic final states.

We illustrate the $\bar{b}q \rightarrow \eta' + \bar{s}gq$ transition and $\bar{s}gq \rightarrow \bar{s}\bar{\mathbf{D}}\mathbf{D}q$ evolution in Fig. 1(a) and (b), respectively. Although the $g\text{-}\bar{\mathbf{D}}\text{-}\mathbf{D}$ coupling can be quantified, we shall refrain from introducing further model dependence in baryon formation from, say, $\mathbf{D}q$. Rather, we shall utilize mainly kinematic arguments. Following the example of how a single K may emerge from $\bar{s}gq$, we take m_g as an effective mass in final state phase space to correspond to $\bar{q}q$ or $\bar{\mathbf{D}}\mathbf{D}$ formation thresholds. For $m_g \lesssim 0.6$ GeV $\lesssim 2m_q$, where m_q is the constituent quark mass, one can view that the gluon “has no place to go”, hence it could only end up in the K meson, as argued earlier. For 0.6 GeV $\lesssim m_g \lesssim 1.1$ GeV $\lesssim 2m_s \sim 2m_{\mathbf{D}}$ (we treat m_s and $m_{\mathbf{D}}$ as roughly equal), the “gluon” can only split into $u\bar{u}$ and $d\bar{d}$, and one has non-resonant formation of $K\pi$, $K2\pi$, etc., or the formation of $|K_g\rangle = |\bar{s}gq\rangle$ hybrid mesons. For $m_g \gtrsim 1.1$ GeV, not only $u\bar{u}$, $d\bar{d}$ and $s\bar{s}$ are open, so is $\bar{\mathbf{D}}\mathbf{D}$. Until effective m_g becomes very massive, say beyond 1.8 GeV, diquark pair formation is on similar footing with $q\bar{q}$ and is not factor suppressed.

We depict in Fig. 2 the regions separated by $m_g = 0.6, 1.1$ and 1.8 GeV. Counting spin degrees of freedom only, we estimate that roughly $1/13$ and up to $3/7$ (depending on scalar or vector diquark nature) of the rate in the 1.1 GeV $\lesssim m_g \lesssim 1.8$ GeV domain corresponds to $\bar{s}\bar{\mathbf{D}}\mathbf{D}q$ final state. For $m_{X_s} < 2.3$ GeV (the recoil peak in anomaly model), phase space and kinematics considerations suggest that this final state would preferentially end up in two body $\bar{\mathbf{B}}_s\mathbf{B}$ final states, given that the $\bar{\Lambda}p$ threshold is at 2.05 GeV. It is likely that one would receive threshold enhancement since diquark pairs are already produced to the right of the $m_g \simeq 1.1$ GeV curve. The modes to search for are therefore $B \rightarrow \eta'\bar{\Lambda}N$ and similar low lying $\bar{\mathbf{B}}_s\mathbf{B}$ states accompanying a relatively fast η' . We stress that the reconstruction of

$\eta'\bar{\mathbf{B}}_s\mathbf{B}$ modes should be easy and with little background, since the $\Lambda_c^+\bar{N}$ threshold does not open up until 3.22 GeV. It therefore may offer an important probe into the higher mass m_{X_s} spectrum not afforded by $X_s = K + n\pi$ modes. One can in principle pursue the inclusive study of $B \rightarrow \eta'\bar{\Lambda}N + n\pi(\gamma)$, where γ could come from e.g. $\Sigma \rightarrow \Lambda\gamma$.

The picture we outline above bears some similarity with the explanation for the low $p_{J/\psi}$ “bump” in the feed-down subtracted inclusive primary J/ψ momentum spectrum seen by CLEO [18]. The excess for $p_{J/\psi} < 0.6$ GeV is suggested [16] to be $B \rightarrow J/\psi\bar{\Lambda}p$ where there is only 128 MeV available kinetic energy. It is known that $B \rightarrow J/\psi + X$ decay has a large component coming from $\bar{c}c$ color octet. Although this excess color is not necessarily shed by a single gluon as in our anomaly model diagram, kinematic arguments were also used to argue for $\bar{\Lambda}p$ in final state. The enhancement may come about because nonperturbative effects are operative for such low kinetic energy. It should be noted that, because of the latter, the detection of $\bar{\Lambda}p$ system recoiling against J/ψ would not be easy. In the anomaly model mechanism for explaining fast η' production in B decays as we outlined above, the X_s recoil system has m_{X_s} peaked at 2.3 GeV. On the one hand this is not far above $\bar{\Lambda}p$ threshold so one again does not expect the opening of many channels. On the other hand, the $\bar{\Lambda}$ and p baryons have considerable kinetic energy since they are recoiling against an energetic η' , the energy of which is (conjectured to be) fed by the $g^*g\eta'$ vertex. Thus, discovery of $B \rightarrow \eta'\bar{\mathbf{B}}_s\mathbf{B}$ modes with energetic η' may be more straightforward than detecting $B \rightarrow J/\psi\bar{\Lambda}p$, and it may also give credence to the anomaly mechanism itself.

An alternative approach offers complementary support for our discussion above from a different perspective. Using naive factorization and simple pole model ideas, the $B \rightarrow \eta'\bar{\Lambda}p$ decay is seen (Fig. 3(a)) as occurring in two steps: $B \rightarrow \eta' + “K”$, followed by $“K” \rightarrow \bar{\Lambda}p$, where “ K ” denotes an off-shell kaon. The first vertex can be normalized to the observed rate for $B \rightarrow \eta'K$, but it is very difficult to make reliable statements about the strength of the dimensionless K - p - Λ effective coupling, g_{beff} . The crude approximation of $g_{beff}^2/4\pi \approx 0.3$ gives $\Gamma(B \rightarrow \eta'\bar{\Lambda}p)/\Gamma(B \rightarrow \eta'K) \approx 0.3$, comparable to the estimate made above through diquark arguments.

Although the simple factorization and pole model ideas are far from reliable, fortunately, some very recent results from CLEO offer support for the above number. Following a suggestion by Dunietz [19], the first exclusive B decays to nucleons have just been observed, with [13] $B^0 \rightarrow D^{*-} p \bar{n}$, $D^{*-} p \bar{p} \pi^+ \approx 1.45 \times 10^{-3}$, 6.6×10^{-4} , respectively. As illustrated in Fig. 3(b), starting from $B^0 \rightarrow D^{*-} \pi^+$, $D^{*-} \rho^+ \approx 2.8 \times 10^{-3}$, 6.7×10^{-3} , with effective couplings analogous to K - p - Λ case above, one easily attains order of magnitude understanding of the large strength of $D^{*-} N \bar{N}(\pi)$ modes. In general, CLEO's observation of sizable exclusive $B \rightarrow \bar{D}^* N \bar{N}(\pi)$ decays that are not far below $B \rightarrow \bar{D}^* \pi$ gives strong support to our argument that $B \rightarrow \eta' \bar{\Lambda} N(\pi)$ may not be far lower than $B \rightarrow \eta' K$!

The situation with regard to $B \rightarrow \bar{\Lambda} p \gamma$ is quite similar in the pole model picture, except K is replaced by K^* . Similar estimates as above again give $\Gamma(B \rightarrow \bar{\Lambda} p \gamma) / \Gamma(B \rightarrow K^* \gamma) \approx 0.1 - 0.3$. These estimates place the baryonic branching ratios with η' and γ in the range of $10^{-5} - 10^{-6}$ and therefore within reach of the luminosities of the B -factories. As in the $\eta' \bar{\Lambda} p$ case, we stress that the final states $\gamma \bar{\Lambda} p(\pi)$, with energetic photon characteristic of $b \rightarrow s \gamma$, are reconstructible, clean and should have little background.

It is tempting to extend the pole model picture further into $B \rightarrow \ell^+ \nu + \bar{\mathbf{B}} \mathbf{B}(\pi)$ via π/ρ poles. In principle, similar numbers would follow. We caution, however, that, unless E_ℓ or $m_{\ell\nu}$ are large, the energy release may not be reduced sufficiently. Furthermore, charmed baryon production in semileptonic B decays, where one has reduced energy release, is relatively suppressed [20]. In particular, $\Gamma(B \rightarrow \bar{p} e^+ \nu + X) / \Gamma(B \rightarrow e^+ \nu + X) < 0.015$ [20] suggest that $B \rightarrow \ell^+ \nu + \bar{\mathbf{B}} \mathbf{B}(\pi)$ may be less promising than in association with fast η' or γ .

Before we conclude, let us review, in descending order of inclusive rate, the processes to be studied for charmless baryonic B decays. The $B \rightarrow J/\psi + X$ process is at 1% level. In some sense it is not really a charmless final state, and has very limited phase space for $X = \bar{\Lambda} p$ (the *only* possibility). Interestingly, a distortion or a bump in the low J/ψ momentum region is found, indicating that $B \rightarrow J/\psi \bar{\Lambda} p$ could be of order 4% – 5% of $B \rightarrow J/\psi + X$ rate. But this mode is not easy to reconstruct because of the very slow proton. The charmless $B \rightarrow \ell^+ \nu + X_u$ process is at 10^{-3} level, but, as mentioned, a bound already exists indicating

that charmed baryon content of $B \rightarrow \ell^+ \nu + X_c$ is less than 1.5% of semileptonic rate. Hence charmless baryon content of semileptonic decays may be less promising. The $B \rightarrow \eta' + X_s$ process is at 10^{-3} level, and, if anomaly mechanism is correct, we expect X_s to be of order 10% or more composed of $\bar{\mathbf{B}}_s \mathbf{B}(\pi)$, with supporting arguments from pole models as well as the newly observed $B \rightarrow D^* N \bar{N}(\pi)$ modes. Hence $B \rightarrow \eta' \bar{\mathbf{B}}_s \mathbf{B}(\pi)$ should be searched for. The $B \rightarrow \gamma + X_s$ is at 3×10^{-4} level. Although one only has the pole model argument to suggest the possibility of sizable baryonic recoil, it again should be studied.

It should be stressed that, besides yielding useful information for theory about the dynamics of weak decays, the observation of baryonic final states suggested here could open up a new direction of studies. It is well known that the decay of the Λ self-analyzes its spin, which can be important for studying CP - or T -violation. In particular, use of the Λ spin will allow one to construct CP -odd, T_N -odd observables such as $\mathbf{s}_{\bar{\Lambda}} \cdot (\mathbf{p}_p \times \mathbf{p}_{\bar{\Lambda}})$, which are driven by the real (or dispersive) part of the Feynman amplitude and not by the imaginary (or absorptive) part of the amplitude, as is the case for a CP -odd, T_N -even observable, such as partial rate asymmetries. Since η' and photonic modes are dominantly loop-induced hence sensitive windows on new physics, such probes may turn out to be very useful.

In conclusion, we point out that $B \rightarrow \eta' + \bar{\mathbf{B}}_s \mathbf{B}(\pi)$ could be the most promising charmless baryonic modes. The η' should still be fast, and for m_{X_s} that is not far above $\bar{\Lambda}p$ threshold, the baryonic recoil system is simple and of low multiplicity. These modes not only could be the first charmless baryonic modes to be detected, their detection could strengthen the anomaly picture, and provide new probes for CP and T violation by bringing in the powerful self-analyzed Λ spin observable. Though the argument gets a bit less compelling, a parallel program should also be started to reconstruct baryonic modes in the recoil system against the photon in $B \rightarrow \gamma + X_s$. The traditional search for two body $B \rightarrow \bar{\mathbf{B}}_{(s)} \mathbf{B}$ modes of course should continue, but observation of rare charmless baryonic B decays proposed here could open a new program for the study of interplay of weak and strong dynamics, and offer very important probes of new CP and T violation observables.

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FIGURES

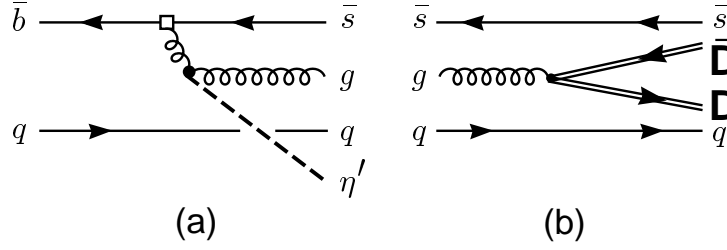


FIG. 1. Diagrams illustrating baryon formation via (a) the $\bar{b}q \rightarrow \eta' + \bar{s}gq$ transition, followed by (b) $\bar{s}gq \rightarrow \bar{s}\bar{\mathbf{D}}\mathbf{D}q$ evolution, where \mathbf{D} denotes a diquark.

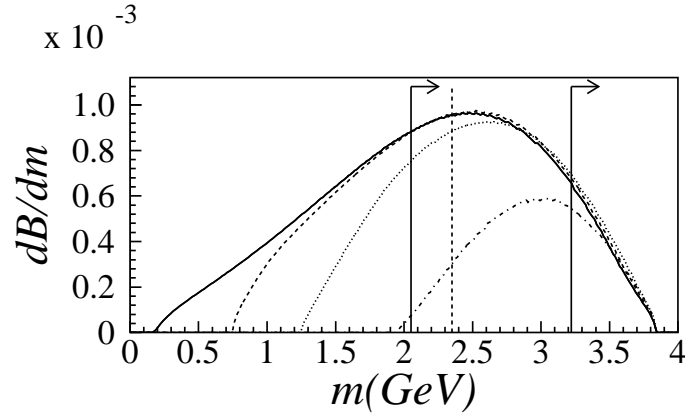


FIG. 2. Illustration for phase space argument of η' + baryon pair formation following the mechanism of Fig. 1. Solid, dash, dots and dotdash curves correspond to taking $m_g = 0, 0.6, 1.1, 1.8$ GeV in phase space. The “gluon mass” of 0.6 (1.1) GeV mark the opening of $u\bar{u}, d\bar{d}$ ($s\bar{s}, \bar{\mathbf{D}}\mathbf{D}$) thresholds, while beyond 1.8 GeV, diquark pair formation may suffer from form factors. The dotted vertical line indicates the experimental cut on $m \equiv m_{X_s}$ in $B \rightarrow \eta' + K + n\pi$ search, while the two solid vertical lines to the left and right corresponds to the $\bar{\Lambda}N$ and $\Lambda_c^+ \bar{N}$ thresholds of 2.05 and 3.22 GeV, respectively.

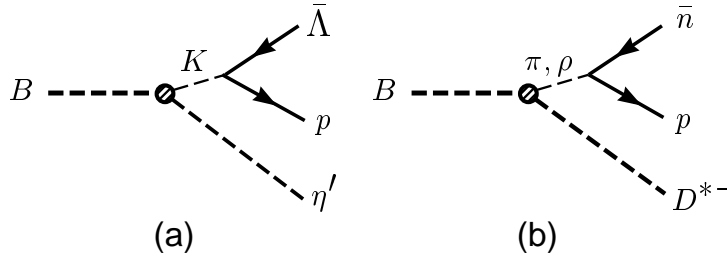


FIG. 3. Pole model diagrams illustrating (a) $B \rightarrow \eta' \bar{\Lambda} p$ and (b) $B \rightarrow D^{*-} \bar{n} p$ production as mediated by $B \rightarrow \eta' K$, and $B \rightarrow D^{*-} \pi, D^{*-} \rho$, respectively.